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Element mixing in the Cassiopeia A supernova[★]

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Abstract. Thanks to mid-infrared observations, we provide new clues to the element mixing during a supernova explosion by probing the mixing between three adjacent layers: the oxygen burning products layer (sulfur, argon,...), the silicate layer and the neon layer. The silicate and neon layers are both contaminated by sulfur and argon in a macroscopic way, but appear segregated, so that the mixing is heterogeneous. This finding complements the microscopic mixing information deduced from presolar grains found in meteorites and implies that, at present time, supernovae are probably not the main dust factory in the Galaxy. The mixing is often interpreted in terms of hydrodynamical instabilities driven by the outward shock following the implosion of the supernova core. Testing whether such instabilities can lead to the injection of material from a layer into upper layers without complete mixing, as suggested by the observations presented in this paper, should be possible with the intense lasers which are starting to be used to simulate astrophysical plasmas.

Key words: Mixing – Supernova remnant – Dust – Forbidden Lines – Cas A

1. Introduction

Supernovae (SNe) are key objects in the Universe (review by Trimble 1983 and references therein). They are the factories which feed the interstellar medium with many of the heavy elements. These heavy elements are built up, layer by layer, inside massive stars, stratified according to the atomic number (review by Arnett 1995 and references therein). Freshly ejected supernova material can be directly observed in the Cassiopeia A supernova remnant. The Cassiopeia A (Cas A) SuperNova Remnant (SNR) is

the youngest SNR known in our galaxy. The SuperNova (SN) exploded about 320 years ago (Fesen, Becker and Goodrich 1988) at a distance of about 3.4 kpc (Reed et al. 1995). It must have been subluminal and/or heavily obscured, since it passed unnoticed, except perhaps by Flamsteed in 1680 (Ashworth 1980). The progenitor of the SN was a massive star (Vink, Kaastra and Bleeker 1996, Jansen et al. 1988, Fabian et al. 1980), probably of Wolf-Rayet type (Fesen, Becker and Goodrich 1988).

The freshly ejected SN material has been widely observed in the optical range (Baade and Minkowski 1954, Chevalier and Kirshner 1979, van den Bergh and Kamper 1985 and earlier papers). The SN material is spatially distributed in Fast Moving Knots (FMKs) (see Figure 1) with a typical speed in the 5000 km/s range, as deduced from their proper motion on the sky and from the Doppler shift of the lines emitted by them. The optical observations have revealed the presence in these knots of heavy elements such as oxygen, sulfur, argon, but no hydrogen or helium lines. Mid-Infrared (Mid-IR) observations of the FMKs have only started recently thanks to observations with ISO, the Infrared Space Observatory (Kessler et al. 1996); these observations have revealed the presence of two additional key components: neon and silicate dust (Lagage et al. 1996, Arendt, Dwek and Moseley 1999).

In this paper, we present a new set of spectro-imaging observations made with ISOCAM (Cesarsky et al. 1996), the camera on board of ISO; these observations reveal the spatial distribution of the silicate knots and of the neon knots. The comparison of these distributions brings unique information on the degree of mixing of the various elements which has occurred during the supernova explosion. Section 2 presents the data, the data reduction and the results we obtain. In Section 3, we discuss the implication for the mixing in SNe.

2. Observations and results

The observations were performed on December 5th 1996 with ISOCAM. The pixel field of view of the instrument was set to 6", comparable to the diffraction limit of the telescope. The total field of view is 3'x3' and the field was

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[★] Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA, and on observations obtained at the Canada-France-Hawaii Telescope.

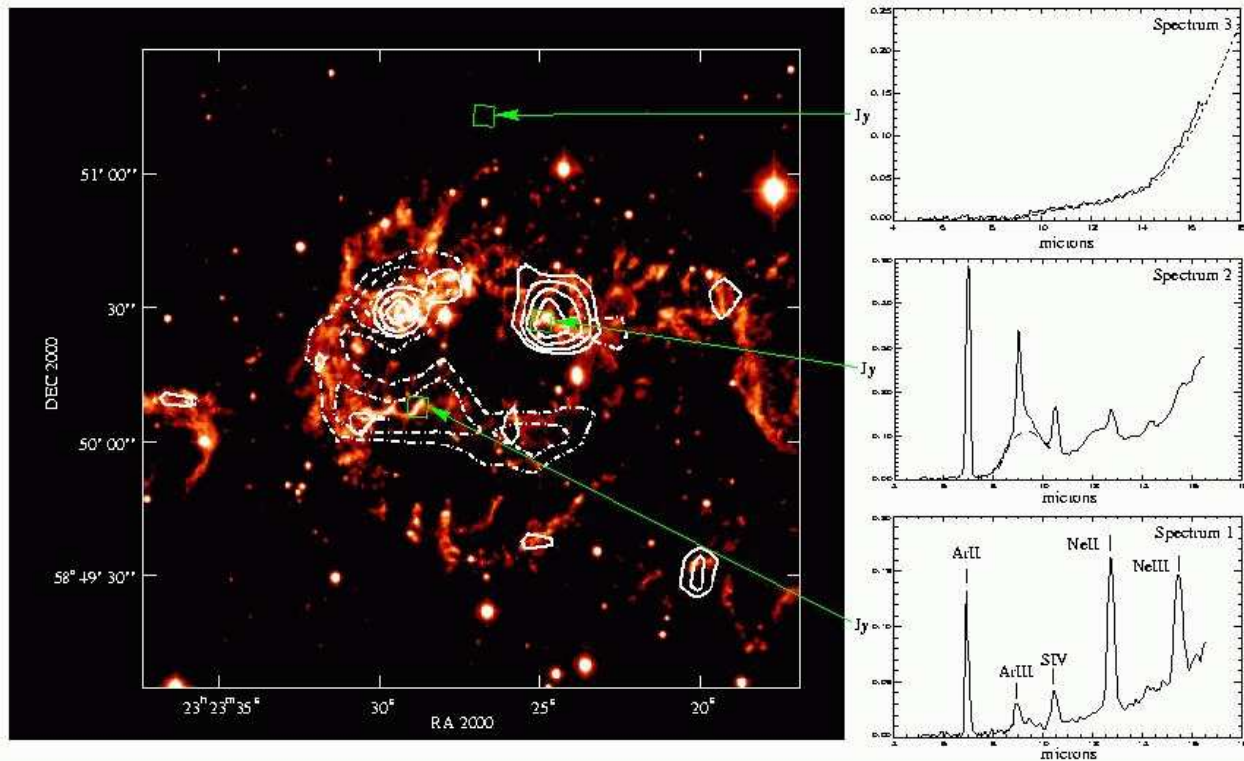


Fig. 1. Contour maps of the [Ne II] line emission (dotted contours) and of the $9.5\mu\text{m}$ silicate dust emission (full contours) overplotted onto an optical image of the Cassiopeia-A supernova remnant. At each contour level the flux is divided by a factor 1.5; (instrumental ghost effects were taken into account to limit the lower contours of neon). The neon line and silicate emission are deduced from spectra such as those on the right of the image (see text). The spectra have been obtained with ISOCAM at a spatial resolution of $6''\times 6''$; the ISOCAM pixel corresponding to the spectrum is represented on the image by green squares. The optical image has been obtained with the SIS instrument at CFHT.

centered on the northern part of the remnant. For each pixel, we have a spectrum from 5 to $16.5\mu\text{m}$ that was obtained by rotating the Circular Variable Filter of ISOCAM; the spectral resolution obtained this way is around 40. The data reduction was performed with CIA¹, using a full spectroscopic data set of an off-position field to subtract the zodiacal contribution. The result consists in 1024 spectra. Some of them are shown on Figure 1. They feature both continuum emission and line emission. The continuum emission rises slowly from 8 to $16\mu\text{m}$; in some spectra, a bump is present around $9.3\mu\text{m}$.

The lines are identified as [Ar II] ($7.0\mu\text{m}$), [Ar III] ($9.0\mu\text{m}$), [S IV] ($10.5\mu\text{m}$), [Ne II] ($12.8\mu\text{m}$) and [Ne III] ($15.5\mu\text{m}$). The argon and sulfur lines were also observed with ISOPHOT (Tuffs et al. 1997), but not the neon lines, which are out of the ISOPHOT-S wavelength range. The neon emission map is obtained by the difference between

the peak flux in the [Ne II] line and the underlying continuum. The evidence for the presence of dust is provided by the continuum radiation underlying the line emission; the silicate dust is well characterized by its feature around $9.3\mu\text{m}$, (see spectrum 2 of Figure 1). The silicate emission map is obtained at $9.5\mu\text{m}$ by subtracting from the detected emission, the emission from a blackbody fitting the data at 7.5 and $11.5\mu\text{m}$. These two maps are both overplotted on an optical image obtained with the SIS instrument mounted on the Canada France Hawaii telescope on August 1998; a filter centered at 6750\AA and with a band-pass of 780\AA was used; the pixel field of view was 0.15arcsec and the integration time was 300s. Note that several optical knots are often present in a single ISOCAM pixel.

Neon, which is barely detected in the visible (Fesen 1990), gives prominent lines in the Mid-IR: the [Ne II] line at $12.8\mu\text{m}$ and the [Ne III] line at $15.5\mu\text{m}$ (see spectrum 1 of Figure 1). Mid-IR searches of neon are

¹ CIA is a joint development by the ESA astrophysics division and the ISOCAM consortium led by the ISOCAM PI, C.J. Cesarsky, Direction des sciences de la matière, C.E.A., France.

more advantageous than optical studies, because of their insensitivity to the relatively high interstellar extinction toward Cas A (typically $A_V=5$, see Hurford and Fesen 1996) and of the lower temperature needed to excite IR lines compared to optical lines. The neon map is compared with the silicate dust map on Figure 1. Spectrum 1 is typical of neon knots. Spectrum 2 is typical of silicate knots (the silicate feature at $9.3\mu\text{m}$ is underlined by the dotted curve). Spectrum 2 is slightly contaminated by neon, certainly due to the strong neon emission just nearby. The bump around this small neon feature could be attributed to Al_2O_3 (Koike et al. 1995, Kozasa and Hisoto 1997).

An anticorrelation between the presence of neon and the presence of silicate in many knots is evident. The regions where both neon and silicate are observed in the IR spectra are confused regions where several bright optical knots lie along the line of sight probed by an ISOCAM pixel ($6''\times 6''$).

The Mid-IR radiation can also be used to probe the presence of argon, through the [Ar II] and [Ar III] lines at respectively 7.0 and 9.0 microns, and of sulfur, through the [S IV] line at 10.5 microns. The lines associated with these two elements show up in almost all the IR spectra, but, given that several knots lie in an ISOCAM pixel, additional arguments are needed before claiming that knots emitting Neon in the IR also contain sulfur and argon. The first argument comes from the IR data themselves. Indeed, even with the poor spectral resolution of ISOCAM observations, it has been possible to measure the Doppler shift of the lines emitted from the knots with the highest radial velocities (Lagage et al. 1999). For these knots, all the lines have the same Doppler shift, indicating a common knot origin of neon, argon and sulfur. Another way to find if neon, sulfur and argon originate from the same knots is to search for oxygen, sulfur and argon lines in optical spectra. Indeed in supernovae the neon layer is associated to the oxygen layer (see Figure 2) and the optical [O III] line has excitation conditions intermediate between those of the IR [Ne II] and [Ne III] lines (same critical density as the [Ne II] line and ionization potential intermediate between those of the [Ne II] and [Ne III] lines). For this purpose we performed follow-up spectro-imaging observations of the Mid-IR knots in the optical at the Canada-France-Hawaii Telescope. Most of the FMK optical spectra feature oxygen, sulfur and argon lines, in agreement with previous studies (Hurford and Fesen 1996, Chevalier and Kirshner 1979). Thus we can conclude that argon and sulfur are indeed present in most of the neon knots. Note also that given that the [Ar III] line and the [Ne II] line have very similar excitation conditions, we can exclude the presence of neon in the silicate knots which emit in the [Ar III] line but not in the [Ne II] line.

Finally, spectrum 3 of Figure 1 originates in a region which is not associated with fast moving knots, but which nevertheless is bright in the IR (and also in X-ray and radio). No line emission is present in the spectrum, and the continuum emission is well fitted by Draine and Lee silicates (Draine and Lee 1984) at a temperature of 105 K (see dashed line in spectrum 3 of figure 1); Draine and Lee graphites do not fit this spectrum. The emission is probably due to circumstellar or interstellar dust heated by the supernova blast wave. Such a continuum emission is present all over the supernova remnant and is probably at the origin of the continuum dust emission underlying the line emission in neon knots. In spectrum 3, no room is left to synchrotron radiation down to the sensitivity limit of our observations, 2.10^{-3} Jansky (1σ) at 6 microns in an ISOCAM pixel. This limit is compatible with the expected IR synchrotron emission (about half a mJy), as extrapolated from the radio synchrotron emission between 1.4 GHz and 4.8 GHz detected in the region of the ISOCAM pixel of spectrum 3 (Anderson et al. 1991).

3. Discussion

In order to explain these observations, we have to recall how the elements are structured inside a supernova. The elements are located in a stratified way according to their burning stage. Neon, silicate making elements and oxygen burning products (S, Ar...) are in different layers (see Figure 2). The hatched region on Figure 2 is what we call the "silicate" region; this is where sufficient amounts of oxygen, magnesium and silicon are present at the same time, to form pyroxene (MgSiO_3). We consider pyroxene because it is this type of silicate which is predicted by dust formation models (Kozasa, Hasegawa and Nomoto 1991). Furthermore the observation of a $22\mu\text{m}$ feature in Cassiopeia A was attributed to Mg protosilicates (Arendt, Dwek and Mosely 1999) and the $9.3\mu\text{m}$ feature of our spectra (see spectrum 2 of Figure 1) is well fitted with very small grains (less than 0.1 microns) of pyroxene.

Then a straightforward way to interpret the fact that the neon and silicate layers remain spatially anticorrelated in the ejecta is to consider that there has only been weak mixing between those layers during the supernova explosion. In contrast, sulfur and argon have been extensively mixed. The mixing of the sulfur and argon layer with the oxygen layer was already revealed by optical observations; the mixing is known to be extensive, but not complete as some oxygen knots are free from sulfur and some sulfur knots are free from oxygen (Chevalier and Kirshner 1979, van den Bergh and Kamper 1985). The key new result from the Mid-IR observations is that the neon and silicate layers are essentially unmixed, i.e. the mixing is heterogeneous.

The data also suggest that the mixing is mostly macroscopic. Indeed silicon is located in the same layer as sulfur

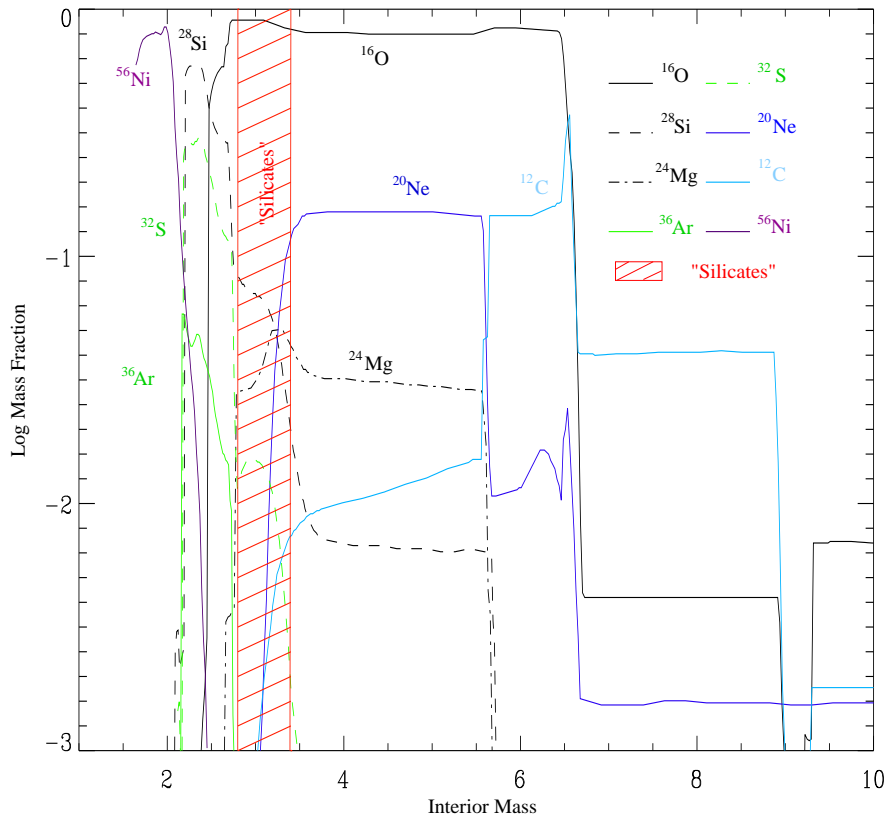


Fig. 2. Layers of elements inside a supernova without mixing; (adapted from Woosley et al. (1995) for a 25 M_{\odot} supernova progenitor; results are similar for a 15 M_{\odot} supernova progenitor). The hatched region is the "silicate" region (see the text).

and argon; thus silicon is also expected to be spread into the neon layer. If the silicon mixing were microscopic, silicates could be produced all-over the magnesium layer, which encompasses the neon layer (see Figure 2); then the anticorrelation of Figure 1 would not hold. Another possibility would be that the mixing is indeed microscopic, but that for some reasons, the silicate production is quenched in the neon layer. In any case the conclusion is that the silicate production from SN is limited to the thin layer shown in Figure 2. As a consequence, the silicate dust production is five times lower than in the case of condensation of all the silicate condensable elements. Silicates are known to be present in large quantities in the interstellar medium, but there is still a debate as to the dominant injection source of these silicates. Supernova ejecta or stellar wind material from giant and supergiant stars have been invoked. Core collapse SNe could be the main silicate provider in case of complete condensation of silicate elements (Dwek 1998). But, if for all core collapse SNe, the condensation is incomplete, as discussed here in the case of Cas A, then core collapse SNe can no longer be the dominant source of silicates at present; but they could have played a dominant role in the past (Dwek 1998). No evidence for dust formation in type Ia SNe has been found so far and no information on the mixing of silicate elements in those SNe exist. In the absence of this evidence, we consider that giant and supergiant stars are likely to be the main silicate providers.

The origin of the mixing is still an open question. Several studies have been made in the framework of the observations of SN 1987A (Arnett et al. 1989 and references therein), the supernova whose explosion in the Large Magellanic Cloud was detected 13 years ago, and of SN 1993J (Spyromilio 1994, Wang and Hu 1994); the issue is how to mix the inner regions where the nickel and cobalt have been synthesized by oxygen explosive burning (see Figure 2) with the upper layers of hydrogen and helium. Hydrodynamic instabilities (of the Rayleigh-Taylor and Richtmyer-Meshkov type) are usually considered as playing a key role. Presupernova models show that the density profile of the presupernova features steep density gradients at the interface of composition changes, especially at the interfaces hydrogen/helium and helium/oxygen; these gradients are regions where shock induced Richtmyer-Meshkov instabilities, followed by Rayleigh-Taylor instabilities, can develop during the SN explosion. Models based on instabilities at these interfaces meet with difficulties to reproduce quantitatively the data (Arnett 1995). It is also hard to imagine how instabilities at the H/He or the He/O interface could be responsible for the heterogeneous mixing presented here, especially if, as generally claimed, the Cas A progenitor has already shed all of its hydrogen and all or most of its helium before the SN exploded. Presupernova models feature another, weaker, density gradient at the bottom of the oxygen layer (for example Nomoto et al. 1997). In addition, convection at work in this region

during the presupernova phase can generate density perturbations which could seed the instabilities (Bazan and Arnett 1998). Thus it seems likely that the mixing originated at the bottom of the oxygen layer, but this remains to be proven by self consistent numerical models following up all phases from pre-supernova to now, taking into account radiative cooling which can lead to clumps.

In complement to advances in numerical simulations, laboratory experiments are needed. Such experiments are starting to be possible thanks to the use of intense lasers, which can generate plasmas mimicking various astrophysical conditions (Remington et al. 1999). Laboratory experiments simulating hydrodynamic instabilities at the H/He interface have already been conducted (Kane et al. 1997, Drake et al. 1998). Experiments reproducing the conditions at the oxygen/oxygen-burning product interface should be performed. The possibility of heterogeneous mixing could be tested.

Another issue which should be investigated is the degree of microscopic mixing versus macroscopic mixing. Heterogeneous microscopic mixing in supernovae is a key requirement in order to explain the isotopic anomalies observed in some presolar grains found in meteorites (Travaglio et al. 1998). For example, the presence of silicon carbide with ^{28}Si implies that ^{28}Si , produced in an inner shell of a SN, has to be injected up to the outer layer of carbon and then microscopically mixed with the carbon. The mixing has to be heterogeneous in the sense that the oxygen layer should not be mixed with the carbon layer; otherwise, the carbon would be locked into CO molecules and no carbon dust particle could be made. Rayleigh-Taylor instabilities mostly lead to macroscopic mixing, but some microscopic mixing could occur at the interface of macroscopically mixed regions. In that context, Mid-IR observations presented here are complementary to meteorite studies.

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